Numerical analysis of rockfall hazard in open pit coal mines

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ABSTRACT: Rockfalls are a significant safety hazard in open pit mines and underground mine entries from open cut highwalls that need to be rigorously managed when designing portal entries for punch longwalls. The installation of restraining nets is a common practice to mitigate this hazard. The protective system however does not totally eliminate the rockfall hazard as blocks can still detach and fall in between the net and the highwall. In such cases it is of prime importance to predict the rock fall trajectories and velocities behind the protective net in order to properly map and assess the residual hazard. An integrated approach combining field testing and DEM is currently being developed for which site specific knowledge of the fundamental characteristics of rockfalls is necessary.

This work presents numerical analyses from which estimations of rockfall motion, trajectories, arrest zones and potential impacting energy on the protection structure are worked out. The study entails the estimation of the size distribution of unstable block first and then the simulation of their trajectories. The former requires an accurate description of the rock mass structure. By combining digital 3D photogrammetry analyses with Discrete Fracture Network modelling it is possible to generate a polyhedral model of the rock mass structure. A modeller capable to automatically identify complex polyhedra (rock blocks) has been used to represent a rock mass with finite persistence discontinuities. Size distribution of unstable blocks and trajectories are assessed performing Monte Carlo analyses where unstable blocks are detected using the key-block method for each realisation. Results are compared with the actual history of rockfall events. This site-specific knowledge will later be used for residual hazard assessment (i.e. trajectories and final velocities behind protective nets).

1 INTRODUCTION

Rockfall hazards cause significant problems worldwide because they are responsible for major damage to infrastructure and even for severe accidents including fatalities. In open pit mines and underground mine entries from open cut highwalls, rockfall events can also have financial consequences should the production be temporarily stopped for safety. If rockfall phenomena have been widely studied for roads and highways (Pfeiffer & Bowen 1989, Giani 1992, Agliardi & Crosta 2003, Dorren 2003) it is only recently that it has been accounted for in the context of open pits and quarries (Alejano et al. 2007, Alejano et al. 2008). However, the possibility of blocks falling behind a temporary protection system such as netting is usually not considered.

For Australian punch longwall operations or any mine entries from the highwall, the standard approach has been the use of rock fall netting combined with face bolting of potentially large joint bounded blocks. At the toe of the highwall, concrete culverts are used as portal structures (Fig. 1). However, the protective system does not totally eliminate the hazard as blocks can still detach and fall in between the net and the highwall. Therefore, an integrated approach combining field testing and numerical analysis by using the discrete element method (DEM) is currently being developed by the authors for which site-specific knowledge of the fundamental characteristics of rockfalls is necessary.

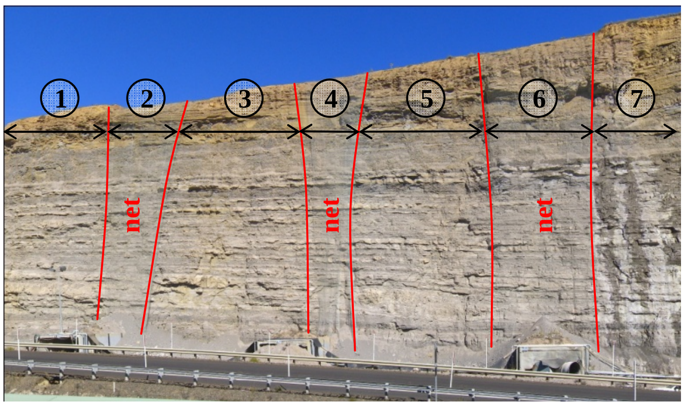


Figure 1. Analysed part of the highwall with 3 portal entries divided into 7 sections.

This paper describes the use of currently available tools for the investigation of the rockfall hazards in open pit mines. A brief introduction into the site specific knowledge of a highwall of an open pit mine is given in Section 2, followed by a description of the structure of the highwall in Section 3. Section 4 describes the analysis of the stability of the highwall by using a generalised polyhedral modeller. Discrete Fracture Network (DFN) techniques combined with geostatistical analysis tools have successfully been used (OPS – Siromodel) to assess the size distribution of the potential unstable blocks. Finally, some results using the 2D rockfall simulation program CRSP (Pfeiffer & Bowen 1989) are presented in Section 5.

2 FIELD INVESTIGATION

A highwall of an un-named coal mine in New South Wales was chosen as project study area. The length of the whole highwall is around 1.4 km. However, only a small part of 85 m with three portal entries has been considered in the present study. The highwall is around 40 m high and around 70° dip. For the analysis it has been divided into 7 sections as it can be seen in Figure 1. Restraining nets are installed on the highwall on top of the underground portal entries in sections 2, 4 and 6. Data on prior rockfall events and associated information on rock material characteristics and block dimensions have been collected during several site surveys at the bottom of the highwall. Table 1 shows number and dimension of the blocks collected. Most blocks exhibited dimensions smaller than 20 cm due to fragmentations during the fall.

Uniaxial compressive strength tests and point load tests have been performed to identify the mechanical properties of the different rock materials present in the highwall. This latter mainly consists of horizontal layers of sandstone and mudstone which are visible in Figure 1.

Finally, geostructural data and digital images of the section of the highwall under consideration have been collected. The software package Sirovision including the modules Sirojoint and Siro3d (http://www.sirovision.com/) has been used to analyse the data. A geo-referenced 3D model of the highwall has been created from the digital images using stereo photogrammetry. These images have been used to map the main structures of the rock mass and to analyse their characteristics. Figure 2, for example, shows the discontinuities identified on the upper part of section 3 of the highwall. Table 2 shows the five main sets of discontinuities that have been identified and used for the structural modelling in the next section.

Table 1. Number and dimensions of blocks at the bottom of the highwall of the sections without net.

Dimension [cm]	Section 1	Section 3	Section 5	Section 7
5 – 9*	29	17	30	20
10 - 19	20	35	33	25
20 - 29	4	14	9	14
30 - 39	0	6	6	1
40 - 49	0	2	1	1
> 50	1	1	1	1

* Blocks with a dimension of less than 5 cm have not been considered.

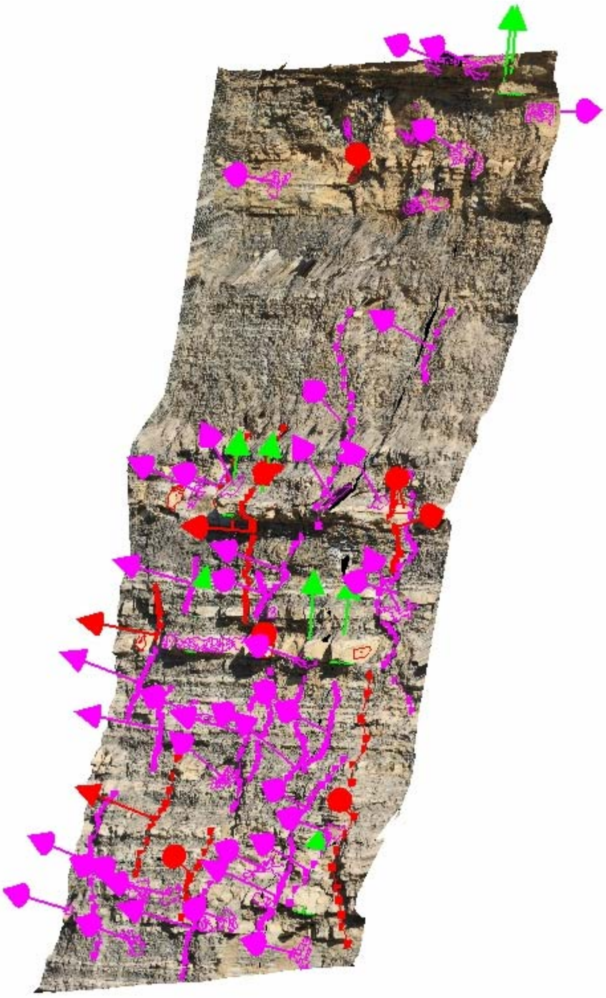


Figure 2. 3D image showing the discontinuities (traces and planes) identified on the upper part of section 3 of the highwall.

Table 2. Characteristics of the discontinuity sets identified in the highwall.

Set	Dip / Dip Direction* [° / °]	Joint Density [m^{-3}]	Joint Intensity [m^2/m^3]
1	19.5 / 63.4	0.021	0.169
2	69.7 / 47.1	0.472	3.733
3	73.5 / 23.7	0.118	0.933
4	63.3 / 41.9	0.027	0.245
5	87.0 / 21.7	0.021	0.214

* Best fit values.

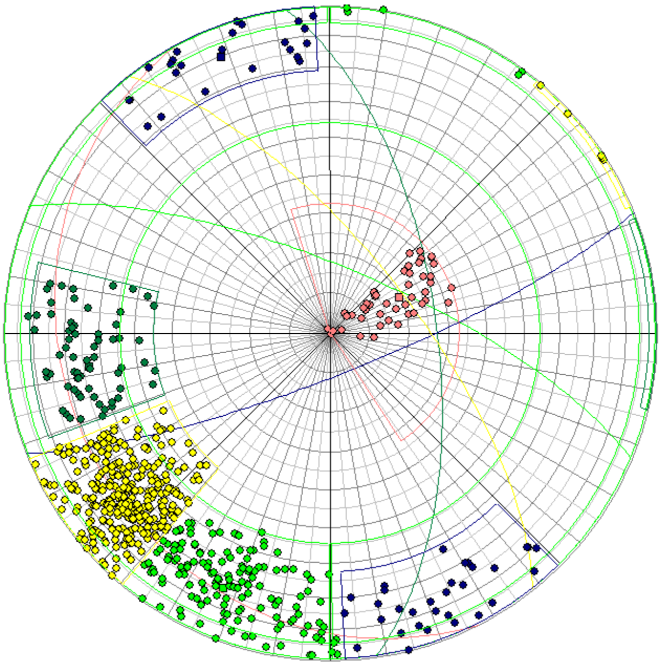


Figure 3. Stereonet representation of the structures of the highwall.

3 STRUCTURAL MODELLING

Prior to kinematic rock fall analyses, developing a representative structural model of the rock mass fabric is essential. Discrete Fracture Network (DFN) modelling explicitly represents how structures identified during field investigation or 3D imaging analyses are spatially distributed within the rock mass (Bonnet et al. 2001). Five sets of discontinuities have been identified during the field investigation and are introduced in the DFN modelling. The sets will intersect forming a distribution of blocks in the rock mass. Size (or volume) and shape of the blocks are controlled by the size distribution of the discontinuities and the spatial density of each set. This latter is defined as the number of centroids per cubic meter. Joint size distribution (or diameter distribution) is adjusted according to the trace length distribution. Joint density can be determined on the basis of orthogonal spacing, number of occurrences (or traces) or fracture frequency (Mauldon 1998, Zhang & Einstein 1998).

Discontinuity size distribution is inferred from the trace data sampled in rectangular windows on the 3D images of the highwall. Assuming circular shaped discontinuities, a relationship between the true trace length distribution and the discontinuity diameter distribution can be derived (Mauldon 1998). The methodology developed by Mauldon (1998) and assorted with maximum likelihood theory by Lyman (2003) accounts for effects of bias and censoring. The same negative exponential distribution of diameters has been used in the present analysis for each set. A series of Monte Carlo simulations has been performed varying the shape parameter of the distribution λ, the minimum cut-off diameter D_{min} and the maximum cut-off diameter D_{max}. The best fit of the trace length distribution is obtained for D_{min} = 0.008 m, D_{max} = 10.014 m and λ = 1.015.

The next step in the DFN generation process is to estimate the fracture density. In this study, the density of each set has been adjusted comparing the number of traces mapped on the highwall to the number of traces generated. Only generated traces longer than 0.35 m have been considered, corresponding to the minimum cut-off length during the mapping exercise. The diameter distribution presented above has been truncated to reduce the number of joints generated. This new distribution with a minimum diameter D_{min} = 2 m will be referred to as the truncated distribution (as opposed to the full distribution, D_{min} = 0.008 m). Fracture density and fracture intensity for each joint set are given for truncated distribution in Table 2. Figure 4 shows the traces of one DFN realisation on a virtual plane corresponding to the highwall.

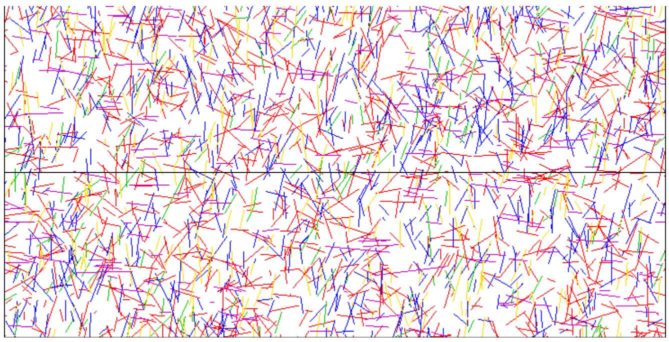
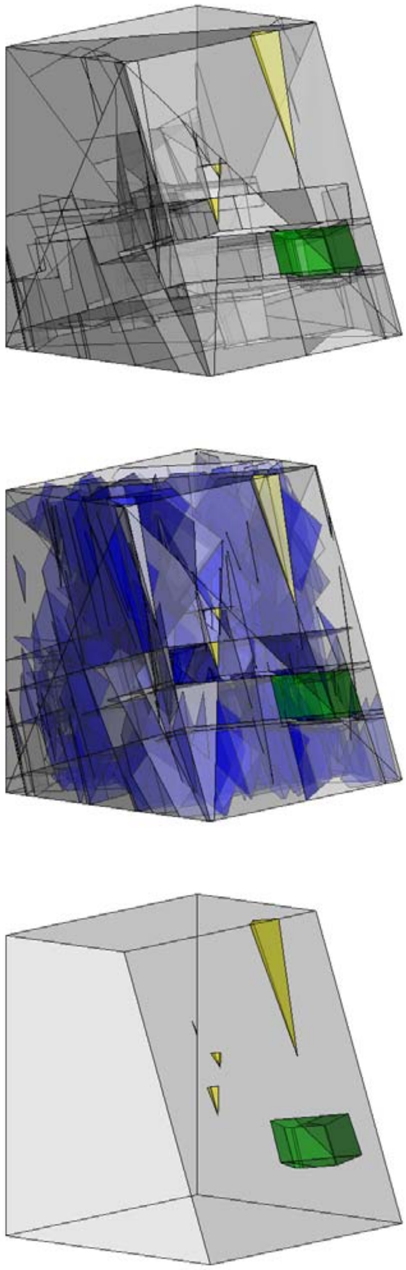


Figure 4. Traces of the generated DFN (total of 2565 traces with 2283 longer than 0.35 m) on the highwall (length of highwall 85 m, height 40 m).

4 POLYHEDRAL MODELLING AND KINEMATIC ANALYSIS

Identification of the polyhedral or rock blocks present in a rock mass structure model is an important tool in the application of block theory and numerical studies of rock mass stability. The polyhedral modeller SIROMODEL (http://www.sirovision.com/) is based on a general structural modelling algorithm (SMA) developed by Elmouttie et al. (2010). It is capable of generating rock mass models involving tens of thousands of fractures, including finite persistence structures, with the formation of thousands of rock blocks. The modeller determines the intersections of 3D polygons as well as the maintenance of vertex, oriented edge and oriented face information so that the resulting three-dimensional polyhedra can be obtained and the key-blocks identified. Exact measures of properties for these polyhedra (e.g. volume, surface area) can then be determined using standard geometric calculations without the need to make assumptions or simplifications about block shape or morphology.

The modelling of the network of discontinuities is performed stochastically. The statistical estimates of orientation, size distribution and density presented in Section 3 are used. Obviously, for such a probabilistic approach to be justified, a number of simulations or DFN realisations must be performed to support any meaningful analysis of the results. Each realisation utilises an entirely new DFN containing sets of joints whose properties (e.g. orientation, radii) have been regenerated stochastically utilising the probability distributions and parameters associated with each property.



(a)

(b)

(c)

Figure 5. Example of a block model created by the SMA: (a) with the surrounding rock mass shown, (b) non block-forming fractures shown and (c) surrounding rock mass hidden.

To construct the model, a cube of rock mass with dimensions 10 m x 10 m x 10 m has been simulated in which the highwall has been excavated (70° slope angle and strike of 320°). The DFNs have been generated inside this prism and the polyhedral modeller has been employed to determine the resulting block structure. Figure 5 shows an example of a block model based on a particular DFN realisation. Figure 5a shows the model with surrounding (unfragmented) rock mass. Figure 5b shows the model including joints that are not involved in block formation (shown in blue). Figure 5c shows only the blocks that have been formed.

The stability of each block against sliding and toppling is then assessed. Each of these events has been categorized according to the Goodman and Shi classification schema (Goodman & Shi 1985) where Type 1 represents instability, Type 2 represents stability assuming stated surface properties and Type 3 represents geometrically stable blocks. Failure events over the various realisations are presented in Figure 6. Most of the blocks appear stable with the current friction angle (20°).

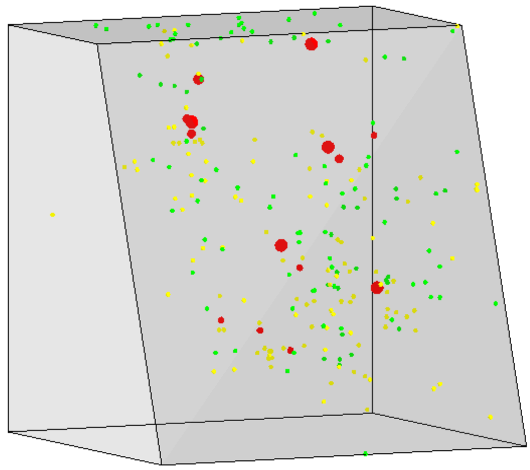


Figure 6. Total failure events for all simulations shown as points in red (Type 1), yellow (Type2) and green (Type 3)

5 ROCKFALL SIMULATION

The 2D rockfall simulation program CRSP (Colorado Rockfall Simulation Program, Pfeiffer & Bowen 1989) has been used to analyse trajectories and final velocities of the potential falling blocks. Analyses have been carried out along a profile of section 2 of the highwall where the net is installed and the residual impact velocity on the portal entry is of main interest.

For this preliminary work, the net has not been taken into account in the analysis. The data obtained will be then used for comparison in the following of the present research where a DEM model will consider the net on the highwall and the residual velocities of the blocks behind the net. In the analyses the blocks are assumed to be circular and their motion is determined by the parabolic equation of free fall and the balance of total energy where rotational and translational energies are considered. Normal and tangential coefficients of restitution, K_n and K_t, are used to take into account the energy dissipation. The program performs a statistical evaluation of the motion by varying the slope angle experienced by the rock on impact according to the ratio *S/R* where *S* corresponds to the surface roughness and *R* to the block radius (Jones et al. 2000).

The analyses have been performed considering typical values for the normal and tangential coefficients of restitution and varying other input parameters such as initial velocity and surface roughness according to the visited site conditions. All the input parameters are listed in Table 3. Different sizes of blocks of two primary materials, sandstone and mudstone, have been used in the simulations. In each simulation 100 blocks have been considered.

Table 3. Input parameters for the rockfall simulation.

Density of sandstone	2400 kg/m^3
Density of mudstone	2100 kg/m^3
K_t for rock mass	0.8
K_n for rock mass	0.4
K_t for concrete culvert	0.95
K_n for concrete culvert	0.7
Initial velocity v_x	0.1 m/s, 0.3 m/s
Initial velocity v_y	-0.1 m/s, -0.3 m/s
Initial y-top starting zone coordinate	45 m
Initial y-base starting zone coordinate	43 m
Diameter *D*	0.3 m, 0.6 m, 1.0 m
*S/R**	1, 1.5, 2
S for concrete culvert	0.1 m

* Defines roughness *S* for the rock mass.

Finally, sensitivity to *S/R*-ratio and block diameter *D* has been investigated. Three analysis points (AP) have been considered along the profile chosen within section 2 of the highwall. The first analysis point AP1 is located at the beginning of the concrete structure, 12 m horizontally from the beginning of the profile. Analysis points AP2 and AP3 are located in the middle and at the end of the concrete culvert, at 16 m and 20 m as indicated in Figure 7.

The initial velocity does not seem to influence the final velocity of the blocks on the culvert as it can be seen from Table 4. This can be attributed to the predominant free fall motion of the blocks along a wall that steep. An initial velocity of $v_x = 0.3$ m/s and $v_y = -0.3$ m/s for sandstone material will be used in the following.

Table 5 summarises the maximal velocity values for the different analyses. It can be seen that both surface roughness *S* and block diameter *D* have a small influence on the velocity only. Figure 8 shows the number of blocks passing the three analysis points for a block with *D* = 0.6 m.

Table 4. Maximum falling velocity for sandstone and mudstone with D = 0.6 m and S/R = 1 for different initial velocities.

Maximum velocity [m/s]	Initial block velocity	
	$v_x = 0.1$ m/s, $v_y = -0.1$ m/s	$v_x = 0.3$ m/s, $v_y = -0.3$ m/s
Mudstone	26.8	26.77
Sandstone	27.1	27.12

Table 5. Maximum falling velocity of a block of sandstone for different *S/R*-ratios and different block diameters *D*.

Maximum velocity [m/s]	Block diameter		
	D = 0.3 m	*D* = 0.6 m	*D* = 1.0 m
S/R = 1	26.77	27.12	26.95
S/R = 1.5	26.69	26.71	26.34
S/R = 2	26.71	26.83	26.62

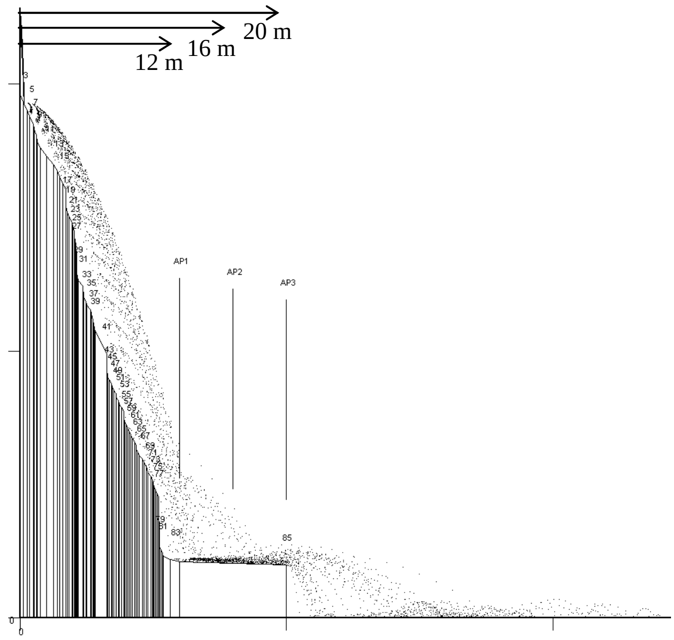


Figure 7. 2D trajectories for a block with *D* = 0.6 m and *S/R* = 1.0.

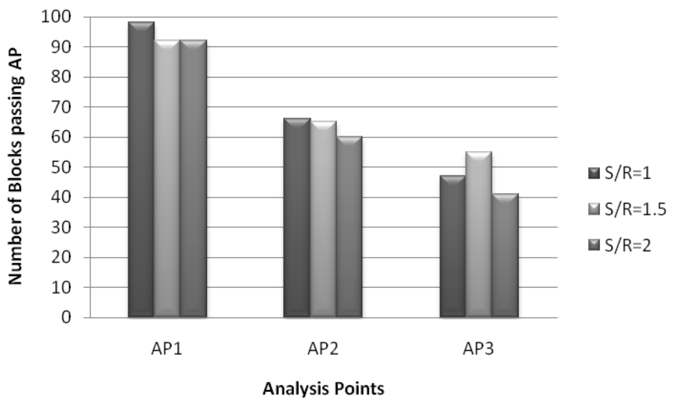


Figure 8. Number of blocks (D = 0.6 m) passing the different analysis points.

It appears that almost all blocks reach analysis point AP1 situated at the start of the concrete culvert and almost 50% of the blocks go beyond the culvert. Therefore, a significant hazard exists and the installation of an effective protective system is essential. Figure 7 shows the 2D trajectories for a block with D =0.6 m and S/R=1.0. The maximum kinetic energy recorded on the concrete culvert for this particular scenario is about 100 kJ. The energy is high enough to damage the concrete structure, and therefore, to disable the entry to the underground mine. It should be mentioned that rock fracturing is not considered in the analyses presented here.

6 CONCLUSIONS

Rockfall poses a significant hazard to entries for punch longwalls in underground mining. Blocks falling from a highwall can easily go beyond the culvert and even destroy the concrete structure, and they can represent a significant safety hazard for the workers of the mine. A protective system has to be installed to mitigate the hazard and to limit the impact energy on the concrete culvert and in the surrounding areas. The installation of protective nettings might be an efficient way to control the rocks falling from the highwall but the rockfall hazard cannot be fully eliminated by using this technique. In fact, the net just reduces the velocity of the blocks, and therefore, the impact on the culvert. However, this is a common used practice but no guidelines exist yet.

The next step is to better understand the real phenomena of a block falling behind a net. Therefore, a 3D numerical model using the DEM is currently being developed by the authors. This will make it possible to analyse the real problem of a block falling between the net and the highwall and to estimate the velocity of the block behind the net and the final impact energy on the culvert which is essential for a safety design of the entry. Numerical modelling will be validated by experimental on site testing. Tests will be performed by releasing blocks from the top of the highwall and recording their velocity and trajectories on sections without the net and sections with net.

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